

(12) INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(19) World Intellectual Property  
Organization  
International Bureau

534 926

(43) International Publication Date  
3 June 2004 (03.06.2004)

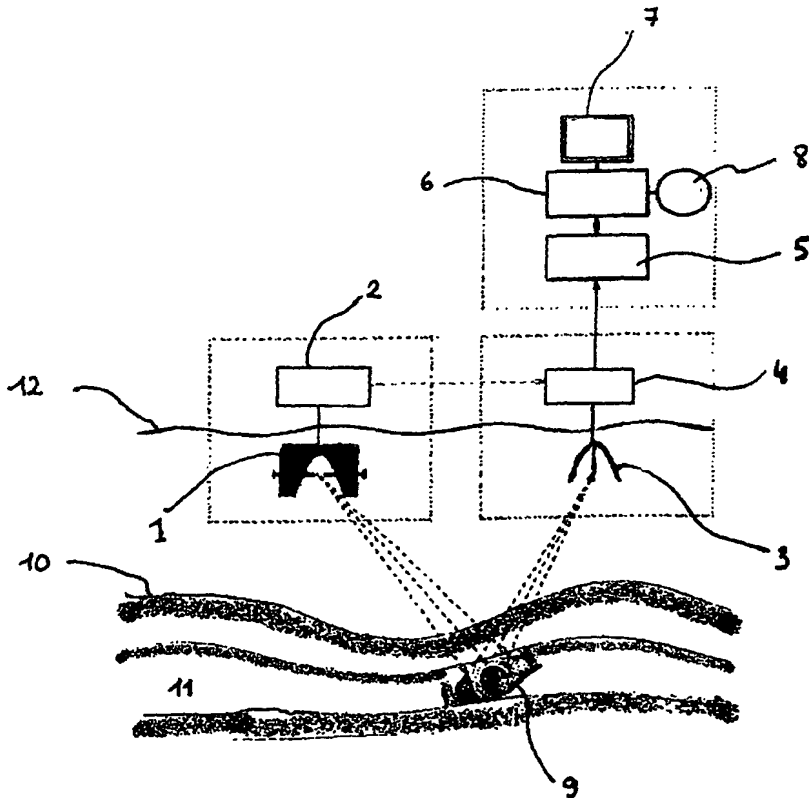
PCT

(10) International Publication Number  
WO 2004/046757 A1

- (51) International Patent Classification<sup>7</sup>: G01V 1/157 (74) Agents: FIAMMENGHI DOMENIGHETTI, Delfina et al.; Fiammenghi Fiammenghi, Via Quatro Fontane 31, I-00184 Roma (IT).
- (21) International Application Number: PCT/IT2003/000751
- (22) International Filing Date: 19 November 2003 (19.11.2003)
- (25) Filing Language: English
- (26) Publication Language: English
- (30) Priority Data: RM2002A000581 19 November 2002 (19.11.2002) IT
- (71) Applicant and  
(72) Inventor: CANNELLI, Giovanni, Bosco [IT/IT]; c/o Istituto de Acustica O.M. Corbino, Via Fosso del Cavaliere 100, I-00133 Roma (IT).
- (81) Designated States (*national*): AE, AG, AL, AM, AT, AU, AZ, BA, BB, BG, BR, BW, BY, BZ, CA, CH, CN, CO, CR, CU, CZ, DE, DK, DM, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, HR, HU, ID, IL, IN, IS, JP, KE, KG, KP, KR, KZ, LC, LK, LR, LS, LT, LU, LV, MA, MD, MG, MK, MN, MW, MX, MZ, NI, NO, NZ, OM, PG, PH, PL, PT, RO, RU, SC, SD, SE, SG, SK, SL, SY, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, YU, ZA, ZM, ZW.
- (84) Designated States (*regional*): ARIPO patent (BW, GH, GM, KE, LS, MW, MZ, SD, SL, SZ, TZ, UG, ZM, ZW), Eurasian patent (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM), European patent (AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HU, IE, IT, LU, MC, NL, PT, RO, SE, SI, SK, TR), OAPI patent (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, ML, MR, NE, SN, TD, TG).

[Continued on next page]

(54) Title: HIGH-RESOLUTION AND HIGH-POWER ULTRASOUND METHOD AND DEVICE, FOR SUBMARINE EXPLORATION



(57) Abstract: A method for underwater exploration which makes use of a parabolic transmitter (1) and a parabolic receiver (3), the transmitter (1) and the receiver (3) being both open at their lower side and immersed below the seawater surface. The electric breakdown discharge occurring between both electrodes (15) of the transmitter (1) generates a primary signal and a pulse which is called "cavitation bubble pulse". The method consists in enhancing the signal (23) produced by the implosion of the cavitation bubble, to the detriment of the primary signal (13''), by appropriately adjusting the value of the "spark gap" (distance *d* between the electrodes) so as to optimise the delay time (*t*) and consequently the acoustic efficiency of the transmitter, by transferring the electrostatic energy to the bubble implosion signal.

BEST AVAILABLE COPY

WO 2004/046757 A1



**Declarations under Rule 4.17:**

- *as to the applicant's entitlement to claim the priority of the earlier application (Rule 4.17(iii)) for the following designation US*
- *of inventorship (Rule 4.17(iv)) for US only*

**Published:**

- *with international search report*

- *before the expiration of the time limit for amending the claims and to be republished in the event of receipt of amendments*

*For two-letter codes and other abbreviations, refer to the "Guidance Notes on Codes and Abbreviations" appearing at the beginning of each regular issue of the PCT Gazette.*

### Description

#### High-resolution and high-power ultrasound method and device, for submarine exploration

#### Technical Field

The present invention generally concerns a high-power and high-resolution ultrasound method used for submarine exploration (survey), and moreover, it relates also to a device for carrying out the same, including a parabolic (that is, paraboloid-like) transmitter of acoustic waves, having a pair of electrodes adequately positioned around its focus, for causing an electric discharge to occur between the electrodes, this discharge being the cause of the generation of the prospecting signal; this device also includes a receiver, having a paraboloid-like configuration as well, and presenting an acoustic pressure sensor localised in its focus, and being appropriately coupled to the transmitter in such a way as to focus the signals that are reflected by objects and by other unhomogeneities buried below the sediments of the seabed. This device or apparatus, is a simplified, but at the same time an innovative and improved version, of an ultrasound ecographic system devised by the same inventor of the present application and disclosed in several "national" patents [Applicant (except US): Consiglio Nazionale delle Ricerche; Inventors: Cannelli G.B., and D'Ottavi E.; Title: "Echographic technique-based method and apparatus to detect structures and anomalies of the subsoil and/or sea bottom and the like": U.S. Patent 4,899,845 (13.02.1990) ; EP 0 320 466 (10.06.92); DE 3 871 922 (3.12.92); Canadian Patent 1,316,249 (13.04.1993)], which has been successfully employed only for soil prospecting at reduced depths, and particularly for archaeological research.

On the contrary, the system of the present patent application has been devised appositely for high-resolution seabed survey, and it is based on the most recent research results obtained at the institute "Istituto di Acustica 'O.M. Corbino' "

making part of the research organisation "Consiglio Nazionale delle Ricerche" (CNR), where the corresponding experiments have been conducted under very advantageous conditions, by using the calibration basin of the Laboratory of Underwater Acoustics.

5

#### Background Art

Several commercial devices of the sonar kind are used in the exploration of the seabed and of its underlying layers, especially in the field of marine geology, in which a high number of researches attempt at obtaining information concerning the nature and distribution of sediments. It is well known that the behaviour of acoustic waves propagating through sediments is more complicated to understand, and, specifically, the absorption of acoustic energy is higher than in the water column, especially in the frequency band corresponding to higher frequencies. Traditional acoustic systems seem inadequate to fulfil all possible environmental situations that may be encountered in the exploration of the upper layers of marine sediments, and this is true in particular during prospecting for archaeological research purposes, for which nowadays no high-resolution acoustic devices exist, having an adequate capacity of penetration into the sediments. To be able to carry out this kind of researches, two important prerequisites exist with regard to the acoustic prospecting pulse, although, unfortunately, they are often antithetic: 1) a high frequency is required in order to obtain a high resolution, so as to be able to visualise irregularities that may even have small dimensions and that are hidden in the upper layers of the sediment; 2) an adequate penetration efficiency is required to perform the detection at greater depths, and this means that lower frequencies and a higher acoustic power must be used. Therefore, one should have at his disposal an acoustic source with a large-band frequency spectrum (e.g. from some kHz, up to some hundreds of kHz), and at the same time, a suitable acoustic power. Actually, commercially available acoustic systems do not fulfil both of these requirements at the same time, and

25

consequently they cannot be utilised in an ample range of experimental conditions and marine environmental situations.

For what concerns a parabolic acoustic source of the "sparker" kind, - which forms part of the above cited echographic system, and which, taken alone, has already been disclosed in other patents of the prior art (see Cannelli G.B. D'Ottavi E., and Santoboni S., Electroacoustic pulse source for high-resolution seismic prospecting, 5 US Patent: 4,734,894, of March 29, 1988; Canadian Patent 1 250 040, of February 14, 1989; EP 0 230 415 (24.07.91); and JP 8755/92, of February 18, 1992) -, while being adequate to focalise the acoustic wave generated by the electric spark, so that 10 the signal transmitted along the principal axis is characterised by a high power in a certain frequency band, it seems unsuited for marine prospecting, because of the following reasons. The acoustic wave generated by that source is characterised by a "primary pulse" which is followed by one or more secondary pulses due to cavitation bubbles that randomly appear in the time domain. This makes it impossible to 15 discriminate the pulses reflected by the seabed, ascribable to objects buried in the sediments, from the signals due to cavitation and which appear as noise. This drawback does not prevent the preceding echographic system from detecting antique cavities formed in the soil, since it suffices in any case - in order to detect said cavities - to receive a signal reflected by the air-soil interface of the cavity, although 20 this signal is disturbed by the cavitation effect (see for instance Fig. 7 of US patent 4,899,845, of February 13, 1990, issued to the same inventors). The same inventor of the apparatus of the present application therefore tried - together with others - to minimise the cavitation signals with respect to the primary signal, by including in the echographic device, in place of a single parabolic source, a suitable tuned array of 25 parabolic sources which had also been disclosed in several "national" patents [Cannelli G.B., D'Ottavi E., Method of high-resolution sea bottom prospecting and tuned array of paraboloidal electroacoustic transducers to carry out such method; JP patent 5-505235 (August 5, 1993), US patent 5,398,217 (March 14, 1995), European

patent 0 491 775 (22.02.1995); Canadian patent 2,065,457 (July 14, 1998)]. By this array one obtains an improvement of the signal in the time domain, but it shows drawbacks such as a lower acoustic efficiency (defined as the ratio between the emitted acoustic energy and the electrostatic input energy), and a considerably  
5 limited frequency band that is insufficient for a high resolution, though the latter is indispensable to detect small findings hidden in the upper layer of the marine sediment; moreover, this apparatus has an excessive cost because it requires a high number of transmission transducers.

Therefore, the objects of the present invention are to provide a method and a related  
10 device, which aim at obtaining a greater acoustic efficiency, a larger acoustic band, a high resolution (so as to discern finds located in the upper layer of the sediments), high power (penetration into the seabed) and a simplified structure (for instance, no third electrode is needed in order to trigger (to strike) the electric discharge between the two electrodes).

15 A further object consists in the reduction of costs to a commercially very attractive level.

#### Disclosure of Invention

The above objects are attained by means of an echographic acoustic method used in  
20 submarine exploration, comprising the following steps:  
the realisation of a parabolic transmitter, which is immersed in water and is open at its base, said transmitter having a thickness sufficient to prevent energy dispersions through its walls and presenting a predetermined focal length, the latter being selected to be sufficiently long so that the expansion of the bubble generated by the  
25 electric discharge occurring between two electrodes that are symmetrically arranged with respect to the focus F, is not hindered by the walls of the paraboloid formed by the transmitter; and wherein said electrodes are adjustable in the direction of the line that joins them, to allow to increase or decrease their reciprocal distance d;

- the realisation of a parabolic receiver, said receiver being open at its base, being immersed in water, and having an acoustic pressure sensor arranged substantially at the focus of the receiver;
- the connection of said transmitter to a unit, having a function of control and energy supply, said unit supplying electrostatic energy to said electrodes and transmitting an electric trigger signal to means of the receiver;
- the connection of said receiver to data processing and display means, for obtaining diagrams of the type of an oscillogram relating to received signals, and/or for obtaining acoustic images;
- and a last step, in which, given a certain value of the electrostatic energy  $E$  to be supplied to the electrodes, and given a certain degree of water salinity, the distance  $d$  between said two electrodes is adjusted so that a maximum delay time  $t$  is obtained between the occurrence of the breakdown electric discharge and a signal due to bubble implosion of the bubble formed during the same discharge; said maximum delay time of the bubble implosion signal being univocally correlated to the maximum acoustic efficiency value, which is given by the ratio between the electrostatic energy  $E$  and the acoustic energy of the bubble implosion signal, and wherein, under these circumstances, the amplitude of the primary signal directly generated by the breakdown discharge is minimal or negligible.
- Furthermore, the invention also relates to the apparatus utilised for the practical realisation of this acoustic echographic method, as defined in the independent apparatus claim.

Specific and advantageous non-limitative variants and embodiments of the acoustic echographic method and of the respective apparatus, form the subject of dependent claims relating to the apparatus and method.

#### Brief Description of Drawings

The present invention will now be described in more detail with reference to the

figures, which show, in an illustrative and non-limitative manner:

Fig. 1, a schematic view of the whole echographic apparatus according to the invention;

5

Fig. 2, the acoustic wave in the time domain, which is generated by a conventional “sparker” source (transmitter);

Fig. 3, the acoustic wave in the time domain, which is generated by a parabolic  
10 “sparker” source, and consisting only of a first signal and a second signal;

Fig. 4, several acoustic signals, in the time domain, emitted by the parabolic (or paraboloid-like) source of the present invention, for varying distances (“spark gaps”) d between the electrodes;

15

Fig. 5, the experimentally established relation, allowing to design a sparker paraboloid-like source (or transmitter) of the “bubble implosion” kind, after fixing the value of the capacity (C) of the condenser bank and after selection of the value of the distance (d) that maximises the delay time between the primary pulse and the  
20 bubble implosion, or in other words, that maximises the acoustic source efficiency;

Fig. 6, an experimental prototype of the echographic apparatus that was installed by the inventor on the basin of the Laboratory of Underwater Acoustics;

25 Fig. 7, a schematic-cross sectional view along a vertical plane, of the parabolic (that is, paraboloid-like) source (transmitter) of the “bubble implosion” kind, forming part of the experimental prototype shown in Fig. 6;



Fig. 8, a schematic vertical cross-section of the parabolic receiver forming part of the experimental prototype shown in Fig. 6;

Fig. 9, the features of the “bubble implosion” acoustic wave generated by the parabolic transmitter, in the time domain (a) and in the frequency domain (b) respectively, wherein Fig. 9(a) gives the amplitude in Volts and Fig. 9(b) gives the relative amplitude in dB (on the ordinate);

Fig. 10 shows an example of a typical test carried out in a laboratory basin, where T denotes the acoustic image of a tube immersed in water at a certain distance from the basin bottom whose acoustic image is B, and specifically, the acoustic pulses of Fig. 10 (a) refer to a situation in which the position of the apparatus (echograph) was taken along the vertical passing through the target (T), and Fig. 10(b) was obtained from 29 complete scanning measurements which made it possible to reconstruct the “acoustic images” T and B;

Fig. 11 shows, in the form of acoustic images, the result of two parallel prospecting operations performed in a shallow seabed, these results highlighting the presence of an antique vault-shaped structure located about 1.5 metres below the seabed, that probably formed part of the buildings of an ancient Roman harbour.

#### Best Mode of Carrying out The Invention

Before going into the details of the research performed by the inventor, we briefly describe, referring to Fig. 1, the apparatus or device of the present invention. This apparatus includes a parabolic transmitter 1, forming the acoustic source, which is associated to an electronic control unit 2. The transmitter 1 is spaced apart from the receiver 3 by an appropriate distance, which is adjustable according to the prospecting depth. The paraboloidal transmitter 1 is energised by means of a

condenser bank (condenser array), not shown in the figures, forming part of the control unit 2. The condenser bank supplies electrostatic energy to the transmitter 1, and the latter converts it into acoustic energy with the aid of the same electronic control unit 2. The receiver, or reception paraboloid 3, is connected to an analog-to-digital converter (ADC) 4 that receives a trigger signal - in the form of an electric signal - from the control unit 2, and transmits the digital data to a microprocessor card (DSP) 5, in order to carry out the successive processing by a dedicated PC 6; the latter displays on the monitor 7 the result of the survey, in the form of an acoustic image of the detected find 9. The numeral 8 denotes a memory used for storing data.

10 The find 9 is buried in the seabed 10, inside the layer formed by the sediments 11. The numeral 12 denotes the seawater surface. It should be noted that in this case, as will be further explained in the following detailed description, the electroacoustic parabolic transducers 1 and 3 are open at their lower side and are completely immersed in water.

15 Now, we will describe the principle on which the invention is based, which originated both from a research performed on small-size models, and from real conditions encountered in the open sea.

Recent results derived from a systematic research made by the inventor on the “cavitation bubble”, have permitted to find a very advantageous solution in the technology of parabolic (that is, paraboloid-like) sources, that was called “bubble implosion” solution. In fact, it was found that by appropriately selecting the electromechanical parameters of the parabolic source it is possible to concentrate in a single pulse a substantial part of the electrostatic energy, and more precisely, to concentrate this energy exactly in that pulse which is generated by the collapsing cavitation bubble and which was previously considered as noise (disturbance). This

20 new method seems simpler and more advantageous than the previous one which was based on an “array”, since it is able to provide - using a single transducer - an acoustic pulse having a greater power and efficiency together with a very wide

frequency band, which cannot be found in any device of the sonar kind actually commercialised. This system is therefore suited to fulfil the two fundamental prerequisites for the exploration (survey) of marine sediments: high resolution, for detecting objects of small dimensions buried in the upper layers, and an adequate power, in case it is necessary to penetrate deeper into the seabed. Moreover, the parabolic transmitter 1 according to the present invention is much simpler and cheaper than the preceding one of the prior art, since it does not require a third electrode interposed between the main electrodes, used to effect a pre-ionisation of the insulating liquid contained in the parabolic cavity, in order to strike the electric discharge (see US patent 4,734,894). In fact, in the present case the paraboloid 1 is directly immersed in the seawater, and since the latter is partially conductive, it allows to strike the electric discharge without any preliminary ionisation of the medium.

Also with regard to the paraboloid-like reception transducer 3, simplifications and improvements have been made compared with the preceding echograph. First of all, the present transducer does not require a neoprene membrane like that used to close the base of the prior-art-paraboloid in order to retain an adequate liquid, since the present paraboloid 3 is also directly immersed in the seawater, as the transmission paraboloid itself. Moreover, the complicated mechanism connected to the piezoelectric sensor, allowing the latter to be positioned at the most suitable location around the focus, in order to receive the acoustic signal, and which was indispensable in prospecting applications of the soil— which is not always perfectly planar —, is now replaced by a simpler external device of the kind of a mechanical articulated joint; the latter being able to appropriately orient the whole paraboloid when it is immersed in water. The portion of this articulated joint on the receiver 3 side is indicated in Fig. 8 by the reference numeral 21.

A brief description will now be given of the physical phenomenon of generation, development, and collapse of the cavitation bubble, and of the technology that allows

to realise a bubble-implosion parabolic source.

After closing the electric circuit of the sparker, an electric discharge flashes between the two electrodes (Fig. 7) positioned on both sides of the focus of the paraboloid, thereby generating a vigorous expansion of the vaporised liquid in consequence of the so developed extremely high temperature gradient. This shock wave 13 (“breakdown”) appearing on the oscillogram as a function of time, in the form of a compression pulse and a subsequent rarefaction pulse, is called “primary” pulse, and in conventional sparker devices its amplitude is higher than, or comparable with, the following pulses 14 which usually are called “cavitation” pulses (see Fig. 2). The first tests performed in water by the inventor, by employing appropriately designed parabolic sparker sources, have demonstrated the possibility of controlling and varying the relative amplitude of the primary pulse 13 with respect to the cavitation pulses 14; in particular, the multiple cavitations 14 can be minimised, thereby simplifying the so-called “signature” of the transmitted signal in such a way that it will contain only two pulses, that is: the primary signal 13’, and the signal 14’ which we will improperly call “cavitation signal” (see Fig. 3). The generation of the second pulse, which is more correctly ascribable to the implosion of a vapour bubble, is interpreted according to a theoretical model developed by the inventor himself and which is supported by experimental tests. This model can be summarised as follows.

The electric discharge generates a plasma, which in turn contributes towards increasing the electric current flowing between the electrodes, and the temperature of the liquid suddenly increases within a volume of only some cubic millimetres (localised in the spark gap between the electrodes); this causes the formation and the harsh increase in size of a vapour bubble that assumes the form of an initial shock wave. This first part of the phenomenon giving rise to the primary signal has a very short duration and is followed by an inertial and slower expansion of the vapour bubble, which, starting from an extremely small dimension, blows up until it reaches a maximum value  $R$  of its radius. Immediately thereafter the bubble starts imploding

towards its centre at a gradually increasing rate, until it has again reached a point-like dimension, which is so small that it can be neglected compared with the maximum value  $R$ . At this time a vigorous inversion of motion occurs, accompanied by a concomitant increase in pressure, that manifests itself as a real explosion. This is the so-called collapse of the bubble, giving rise to the second pulse named "bubble-implosion pulse". The latter occurs when the bubble wall velocity towards the bubble centre reaches a value comparable with that of the sound velocity in the saturated vapour contained in the bubble.

To obtain a parabolic bubble-implosion source, that is, a transducer suited to concentrate almost all of the energy in the second pulse generated by the collapse of the vapour bubble, it is necessary to make use of the experimentally established diagrams derived by the inventor by means of tests performed in the water of a sea basin, and thereafter in a laboratory basin, on parabolic transducers whose electromechanical parameters have been varied appropriately. An example of this is given in Fig. 4, showing a sequence of acoustic signals (relative amplitude of acoustic pressure as a function of time) transmitted by a parabolic sparker source, for different values of the distance (spark gap) between the electrodes, but for the same (constant) value of electrostatic energy. It can be seen that for values of the spark gap exceeding 10 mm, the oscillogram has only one pulse, that is, the one ascribable to the vapour bubble implosion, and that the primary (or breakdown) pulse can be neglected altogether. The former signal disappears however for values of the spark gap exceeding the limit value of 30 mm, since in this circumstance, the conditions for the generation of the temperature gradient required to produce a vapour bubble, do not exist any more. If the spark gap is less than 10 mm, the primary (breakdown) signal appears as well, and this signal contributes to the dissipation of part of the electrostatic energy furnished to the system, thereby reducing the energy available to the vapour bubble.

An important parameter linked to the mechanical energy which is stored in the

vapour bubble and which is subsequently returned in the form of acoustical energy irradiated at the moment the collapse occurs, is the so-called "delay time", that is, the time interval between the breakdown and the appearance of the bubble pulse. This time period is correlated with the acoustic efficiency of the transmission transducer.

5 In Fig. 4, it may be seen - for instance - that when the spark gap equals 25 mm, the delay time attains a maximum, and this corresponds also to a bubble-implosion signal having a maximum amplitude. By analysing different oscillograms analogous to the one shown in Fig.4, but corresponding to different values of electrostatic energy, and obtained under the ideal conditions of systematically performed tests in a  
10 laboratory basin, it was possible to derive an experimental relationship which can be summarised in the graphs of Fig. 5 and in similar ones (not shown) obtained under different conditions of water salinity. This experimental law has been confirmed by the theoretical model of the bubble, and it expresses the delay time as a function of the distance between the electrodes for various values of the electrostatic energy  
15 supplied to the system. The curves of Fig. 5 correspond to a parabolic transducer of reduced size compared with that used in sea water to carry out the tests of Fig. 4, since the former transducer is much more handy when tests are performed in a laboratory basin.

Moreover, the salinity of the water contained in the laboratory basin, which was less  
20 than that of seawater, does not invalidate at all the general validity of the law shown in the graphs of Fig. 5, since the latter are simply translated towards higher values of the spark gap with increasing water salinity. The same figure also shows the values of the capacitance  $C$  of the condenser array (condenser bank) used by the electric control unit, instead of the electrostatic energy values ( $E = \frac{1}{2} CV^2$ ); however the latter  
25 are easily obtainable by the knowledge of the potential difference  $V = 2250$  V applied to the electrodes of the sparker. It can be noted that the time delay, and consequently the acoustic efficiency of the transducer, is not a monotonic function of the distance existing between the electrodes; on the contrary, this time delay reaches

a maximum for a well-defined value of the spark gap, which shifts towards greater values of the spark gap when the capacity – or energy – is increased. These experimental results are in agreement with the following theoretical relation:

$$\eta = 5.455 t^3 [p - p_v(T)]^{5/2} / (\rho^{3/2} E) \quad (1)$$

- 5 The relation (1) expresses the conversion efficiency  $\eta$  of the electric energy  $E$ , in mechanical energy stored in the bubble (taking into account also the irradiated acoustic energy), as a function of the difference  $p - p_v(T)$  between the pressure of the environment and that of the saturated vapour in the bubble at the temperature  $T$ , of the density  $\rho$  of the liquid, and of the delay time  $t$ . The high dependence of the
- 10 efficiency from the delay time is immediately obvious. This relation has been deduced by the inventor from a simpler formula, giving the collapsing time of a bubble of saturated vapour, starting from an initial radius  $R$  until its size-reduction to a negligible dimension, which was first derived by Lord Rayleigh (see Lord
- 15 Rayleigh, "On the pressure developed in a liquid during the collapse of a spherical cavity", Phil.Mag. (1917), vol. 34, pages 94-98) to explain the sound emitted from vapour bubbles formed in a tea kettle.
- Summing up, the relation (1) tells us that for the same electrostatic energy supplied to the system, and for constant pressure and temperature, the increase in the time delay causes a noticeable increase in the conversion efficiency of the electric energy
- 20  $E$  in mechanical energy stored in the bubble, wherein the latter includes the acoustic efficiency of the source. The maximisation of " $t$ " therefore constitutes the fundamental principle on which the method of the present invention is based in order to optimise the efficiency of the bubble-implosion source. To realise this source, in general one proceeds in the following manner. After having manufactured a metallic
- 25 paraboloid of sufficient thickness, so as to prevent energy dispersions through its walls and having a predetermined focal length which is sufficiently long (e.g. greater than 3 cm) to permit a free development of the bubble about the focus, without being hindered by the paraboloid walls, two tungsten electrodes are provided, which can be

adjusted with respect to the focal point by using suitable external means based on micrometer screws. The distance "d" (in mm) between the two electrodes must be selected so as to maximise the acoustic efficiency, that is, the delay time, making use, to this end, of the law shown in the graphs of Fig. 5 (abscissa = spark gap;  
5 ordinate = time delay (ms)), and making use of further graphs that could be derived under other salinity conditions of the water. Once a value of the supply energy has been chosen (corresponding to a well-defined value of the capacitance after fixing of the potential difference applied to the electrodes), the spark gap value corresponding to the maximum value of the delay time is obtained from the graph.

10 As an illustrative but non-binding example of all possible realisations of the present invention, we will describe the features of the experimental prototype represented in the photograph of Fig. 6, which shows the transmission and reception transducers arranged at the edge of the calibration basin of the "Laboratorio di Acustica Subacquea" (underwater acoustics lab). This prototype has been realised appositely  
15 for submarine archaeology applications, which cover depths below the seabed comprised in the interval from some metres up to some tens of a metre; for this reason, the distance between the two transducers is adjusted during the prospecting in the sea, about values that are substantially low (approximately 50 cm). For greater prospecting depths, this distance is suitably increased by making the transducers  
20 slide on an adequate support or mechanical guide. The transmission transducer 1, schematically shown in Fig. 7, has the following geometric dimensions:  
height = 11 cm; inner diameter of the base = 20 cm; focal length = 10 cm. The tungsten electrodes 15 have a hemispheric shape and have a radius equal to 5cm; moreover, they have been arranged at a distance  $d = 25$  mm from each other, so as to  
25 produce, for an energy corresponding to 720 Joule, the maximum delay time, as may also be seen from the oscillograms of Fig. 4 referring to tests carried out in salt water (salinity = 3.4 %) with the same transducer.

The paraboloid has been obtained by turning a massive cylinder 16 of aluminium



(size: 11 cm x 22 cm), which therefore was sufficiently thick to prevent dispersions of acoustic energy due to backward transmission through the walls. The reception transducer, schematically shown in Fig. 8, is made of aluminium as well, and it has the following geometric dimensions: height = 22 cm, inner diameter of the base = 20 cm, focal length = 1.2 cm, wall thickness = about 1 cm. The ceramics 17 which is located at its focus, has a flat frequency response up to about 400 kHz. Now, turning our attention to Figs. 7 and 8, in these figures the numeral 20 denotes the internal parabolic region occupied by the water, numerals 18 denote an insulating coating of the electrodes, numerals 19 denote the spark gap adjusting screws, numeral 16 indicates the aluminium block forming the paraboloid of the source (or transmitter 1): furthermore, numeral 21 denotes the coupling means used to realise the mechanical joint for orienting the receiver 3. The reference numeral 22 denotes the parabolic inner region of the receiver 3, which is occupied by the water.

The graphs of Fig. 9 show typical features of the acoustic wave generated by the transducer prototype of the "bubble-implosion kind", in the time domain (a) and in the frequency domain (b) respectively. The signal has been detected at a distance of 1 metre along the axis of the paraboloid 1 - while the latter was immersed in the water of the laboratory calibration basin -, by using the above described reception paraboloid 3. The supplied electrostatic energy was in this case equal to 506 Joule, and the applied potential difference was 2250 V, while the capacitance was fixed at the value of 200  $\mu$ F. It can be clearly seen that almost all of the acoustic energy irradiated by the transducer 1 is concentrated in the second pulse 23 due to bubble implosion, whereas the primary (or breakdown) signal 13" is nearly negligible.

Moreover, the frequency spectrum shows intense spectral components down to about 50 kHz, and a wide and almost flat frequency interval from 100 kHz up to about 400 kHz, showing variations within some dB. None of commercially available devices of the sonar type is able to generate a frequency band which is so broad, and at the same time so rich in intense components at lower frequencies that are required

to penetrate into the seabed.

In Fig. 10 (a) there is shown a typical test result, obtained in the laboratory basin, in a situation in which the entire ultrasound system was arranged to effect a prospecting above a cylindrical target (diameter = 14 cm) immersed in water at about 1.5 m  
5 above the bottom of the 6-metre deep basin. One may note, in chronological order, the presence of: the primary signal 13''; the bubble implosion signal 23' received laterally and attenuated by the walls of the reception paraboloid; the echo 24 of the target; and, finally, the echo 25 due to the basin bottom.

This oscillogram, forming part of a set of 29 measurements performed during a  
10 scanning above the target, corresponds to a position of the echograph along the vertical passing through the target; however, to obtain an acoustic image of the object it is necessary to adequately process all signals of the whole scanning operation effected above the object. Fig. 10(b) shows the acoustic image of the object obtained in this way, after an appropriate processing of the signal ("beam forming").

15 To this end, the inventor of the present invention has developed a signal processing software for this echograph, suited to provide high-resolution acoustic images, including those relating to macroscopic anomalies of the seabed, and to small targets of simulation experiments performed with scale models in a lab basin. In the latter case, the scale of the models and the frequency region are selected in such a way as  
20 to allow, using physical similarity considerations, to extrapolate the results so that they are applicable to real objects. Actually, though these categories of experiments are different as concerns the involved scale and frequency band, they have in common the same physical approach, that is, the interaction of the acoustic waves with the relevant objects and structures, causing the diffusion and reflection of  
25 acoustical energy suited to provide information which is detectable by means of appropriate sensors. If this information is presented in the form of maps, namely as a planar or tridimensional distribution of an appropriate acoustic parameter (e.g. the acoustic intensity), one obtains so-called acoustic images that have a direct

correlation with the shape and structure of the analysed (or detected) objects. In Fig 11, there are shown two examples of acoustic images obtained by a scanning performed with the present ecograph in a shallow sea basin. These images relate to two parallel scanning operations performed at a mutual distance of 5 m. Some unhomogeneities located below the seabed 26 are visible in these figures, and particularly the vault-shaped structure 27 which appears in both scanning images and which is buried at about 1.5 m below the seabed; this vault-shaped structure presumably formed part of ancient buildings of a harbour of the Roman age, now buried below the sediments.

10

#### Industrial Applicability

Lastly, we mention the most important applications in which the present invention may validly be utilised. The system is so versatile as to permit explorations at low (0-50 m) and medium depths (50-100 m) in the seabed, or even at higher depths, provided it is adequately designed and sized.

This system has been devised principally to permit exploration of anomalies and unhomogeneities in sea sediments, and for all applications involving sediments, such as mineralogical applications concerning the search of metallic nodules or archaeological finds buried in the sediments.

20 However, it could be applied as well in oceanographic explorations, in which high resolutions and powers are required for signal propagation through large distances.

Claims

1. An acoustic echographic method for underwater exploration, making use of the bubble-implosion effect, characterised in that it comprises the following steps:
- the realisation of a parabolic transmitter (1), which is immersed in water and is open at its base, said transmitter having a thickness sufficient to prevent energy
- 5 dispersions through its walls and presenting a predetermined focal length, the latter being selected to be sufficiently long so that the expansion of the bubble generated by the electric discharge occurring between two electrodes (15) that are symmetrically arranged with respect to the focus (F), is not hindered by the walls of the paraboloid formed by the transmitter (1); and wherein said electrodes (15) are
- 10 adjustable in the direction of the line that joins them, to allow to increase or decrease their reciprocal distance (d);
- the realisation of a parabolic receiver (3), said receiver being open at its base, being immersed in water, and having a pressure sensor (17) arranged substantially at the focus of the receiver (3);
- 15 the connection of said transmitter (1) to an electronic unit (2), having a function of control and energy supply, said electronic unit supplying electrostatic energy to said electrodes (15) and transmitting an electric trigger signal to means (4) of the receiver;
- the connection of said receiver (3) to data processing and display means (4,5,6,7,8),
- 20 for obtaining diagrams of the type of an oscillogram relating to received signals, and/or for obtaining acoustic images of these received signals;
- and a last step, in which, given a certain value of the electrostatic energy (E) to be supplied to the electrodes (15), and given a certain degree of water salinity, the distance (d) between said two electrodes (15) is adjusted so that a maximum delay
- 25 time (t) is obtained between the occurrence of the breakdown electric discharge and a signal due to bubble implosion of the bubble formed during the same discharge; said

- maximum delay time of the bubble implosion signal being univocally correlated to the maximum acoustic efficiency value, given by the ratio between the electrostatic energy (E) and the acoustic energy of the bubble implosion signal (23), and wherein, under these circumstances, the amplitude of the primary signal (13'') directly  
5 generated by the breakdown discharge is minimal or negligible.
2. A method according to claim 1, wherein the distance between the receiver (3) and transmitter (1), and/or the energy (E), are all adjusted during prospecting operations according to the depth of the region below the seabed to be subjected to the survey.  
10
3. A method according to claim 1, wherein said electrodes are made of tungsten.
4. A method according to claim 1, wherein the employed pressure sensor (17) is made of a piezoelectric ceramics having a flat frequency response, for instance up to  
15 values of about 400 kHz.
5. A method according to claim 1, wherein the orientation of the receiver (3) may be varied for obtaining a better reception of the echo generated by the reflection of the bubble-implosion signal on the seabed, on the sediments, on an archaeological find,  
20 and/or on an object which is immersed in water at a certain distance from the seabed.
6. A method according to claim 1, including various scanning operations, performed along parallel straight lines in order to obtain an acoustic image, and/or including several measurements, effected along a horizontal line which comprises a position  
25 located on the vertical line passing through a hypothetical object or a possible archaeological find to be detected, analysed, or displayed.
7. A method according to claim 6, wherein the acoustic images, obtained in map

form, namely as planar or tridimensional distribution of an acoustic parameter such as the acoustic intensity, are derived by means of a signal processing software, suited to provide high-resolution acoustic images, and which has been developed on scale models in a lab basin, and wherein the selected model scale and frequency region are  
5 such to permit extrapolation of the results to include real conditions, based on physical similarity considerations.

8. An apparatus for carrying out the acoustic echographic method based on the bubble-implosion effect according to anyone of the preceding claims, comprising:  
10 a parabolic transmitter (1) associated with a control unit (2), the latter being used to supply electrostatic energy (E) to two electrodes (15) arranged substantially symmetrically to the focus (F) so as to face each other at a mutual distance, this distance being adjustable through regulation means (19);  
a parabolic receiver (3), connected to data processing and display means (4,5,6,7,8)  
15 triggered by an apposite trigger signal, said receiver including a pressure sensor (17) which is substantially located at the focus of the receiver (3);  
wherein, the mutual distance (d) between the electrodes (15) is adjusted according to the method claims 1-7, the thickness of the walls of the transmitter (1) renders substantially negligible the bubble implosion signal passing through said walls which  
20 is directly transmitted towards the receiver (3), and the focal length of the transmitter (1) is selected so that it does not hinder the formation of the bubble until it reaches its maximum size (R).

9. An apparatus according to claim 8, wherein said electrodes (15) are made of  
25 tungsten.

10. An apparatus according to claim 8, wherein said regulation means (19) are micrometer screws.

11. An apparatus according to claim 8, wherein said sensor (17) is a piezoelectric ceramics with a flat response up to about 400 kHz.

12. An apparatus according to claim 8, wherein the data processing and display means, which are triggered by an apposite trigger signal sent by the electronic unit (2), include a ADC filter (4), a DSP microprocessor card (5), a dedicated personal computer (6), a display monitor (7) for visualising acoustic images, a memory (8), and possibly also visualisation means for the display, in the form of an oscillogram, of the analogue signal that constitutes the echo.

10

13. An apparatus according to claim 8, wherein the parabolic transmitter (1) forms a block of suitable material, for instance aluminium, and is obtained by means of turning from such block, which may have any suitable form, e.g. cylindrical.

15 14. An apparatus according to claim 8, wherein the receiver (3) has a mechanical articulated joint system allowing its orientation.

15. An apparatus according to claim 8, having a horizontal guide rail for the adjustment of the mutual distance of the electroacoustic transducers (1; 3).

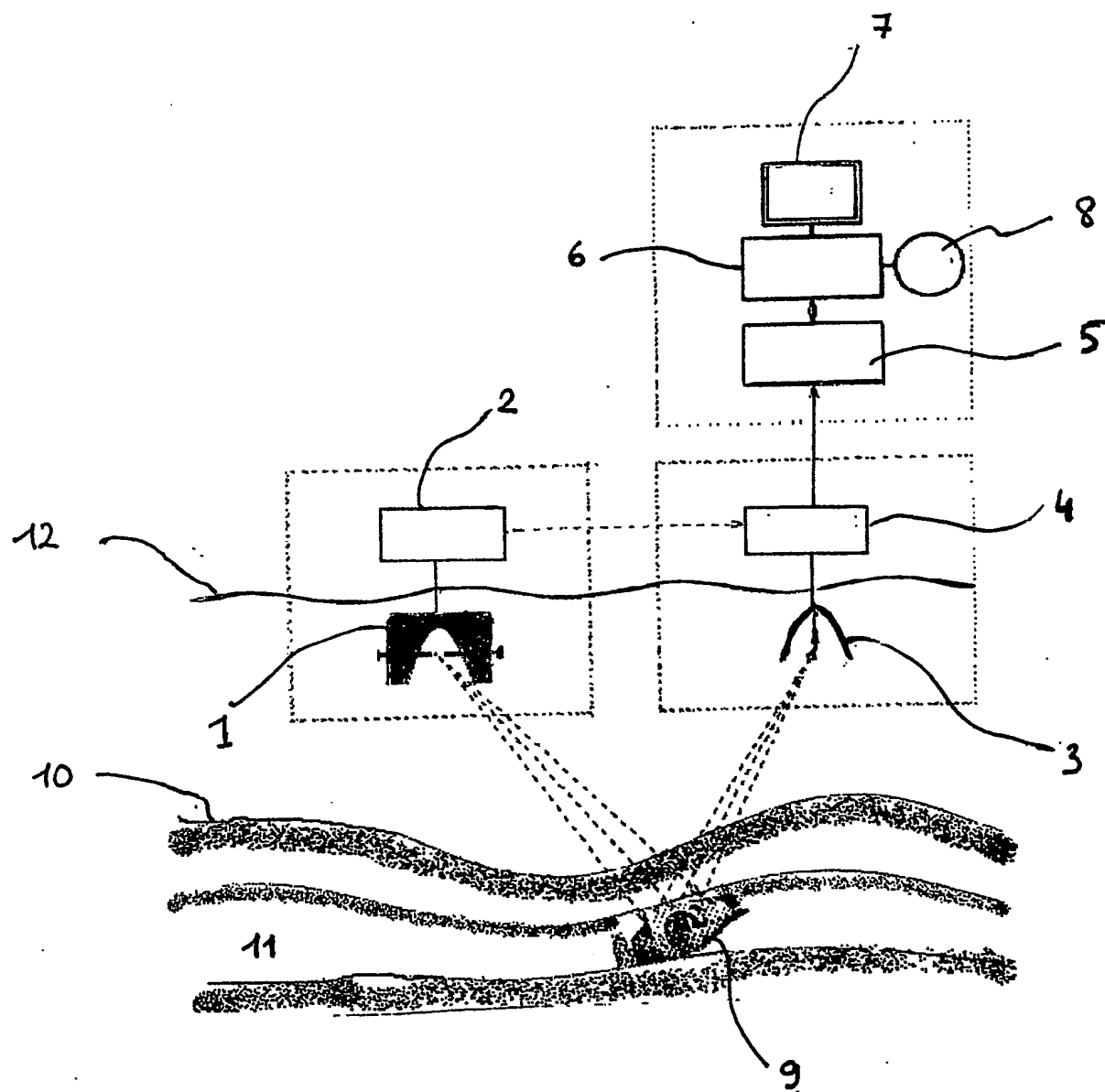


Fig 1



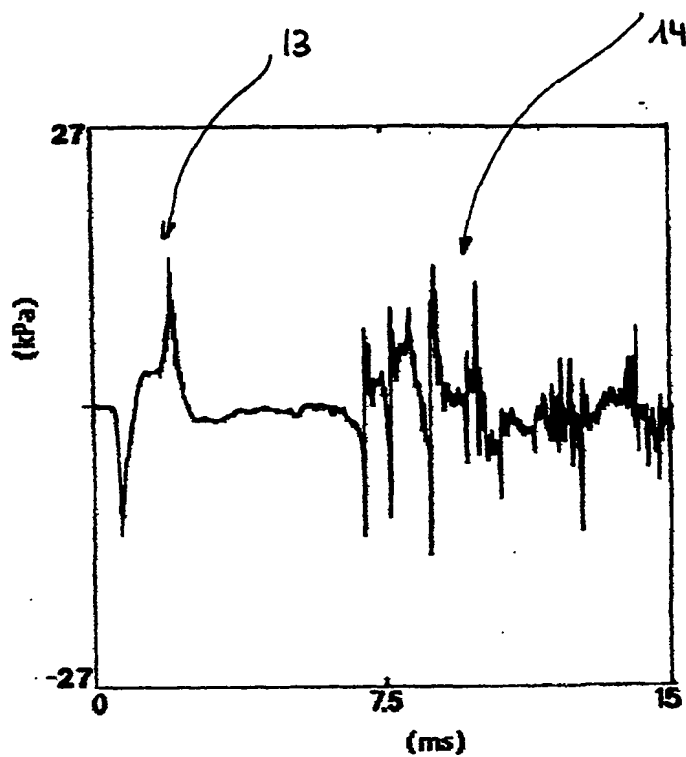


Fig 2

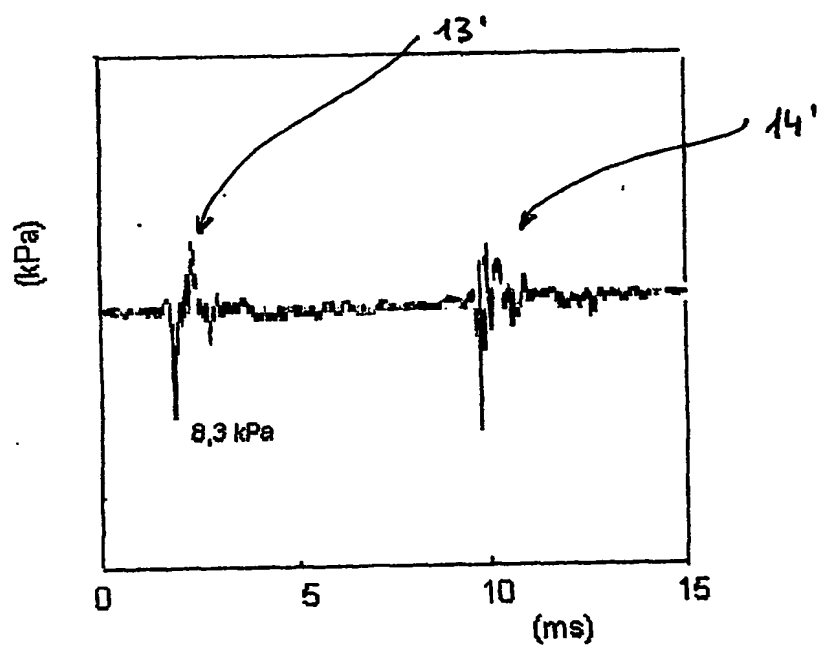


Fig 3

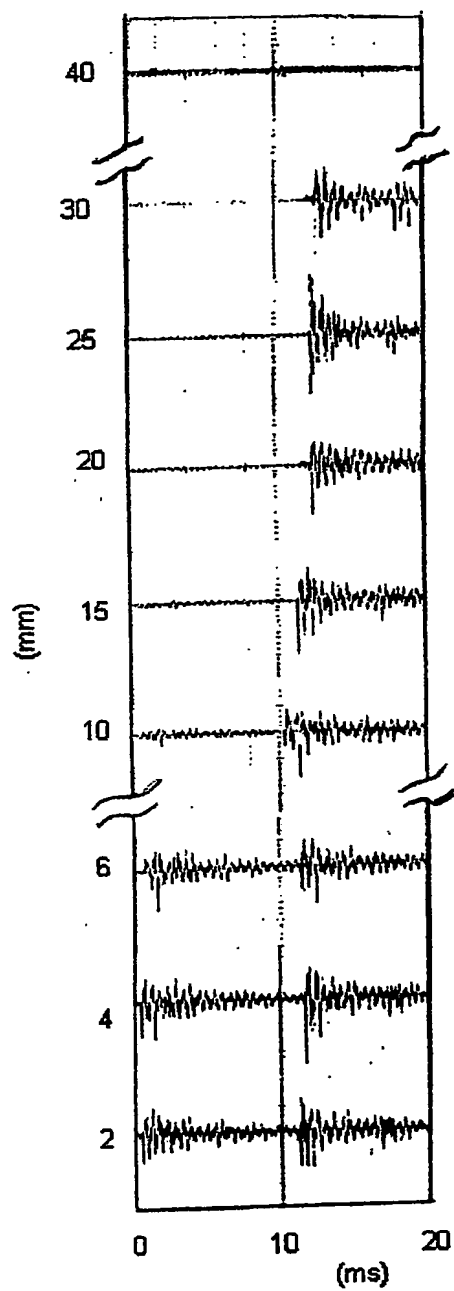


Fig. 4

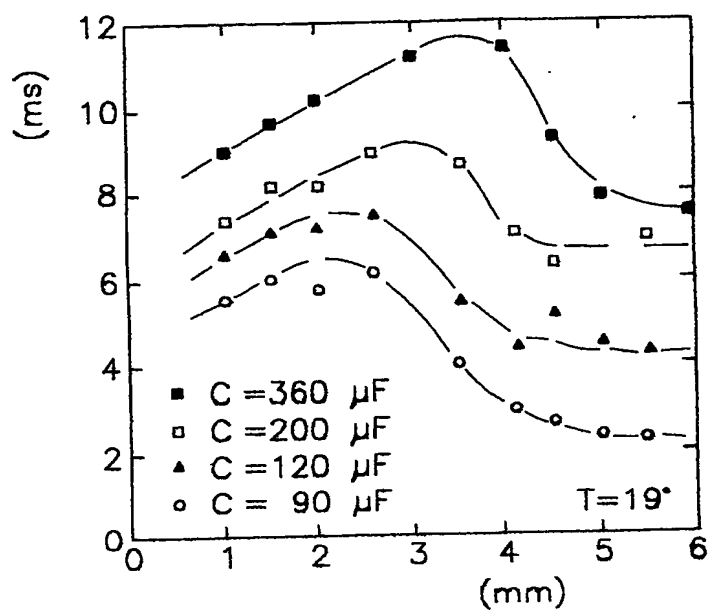


FIG. 5

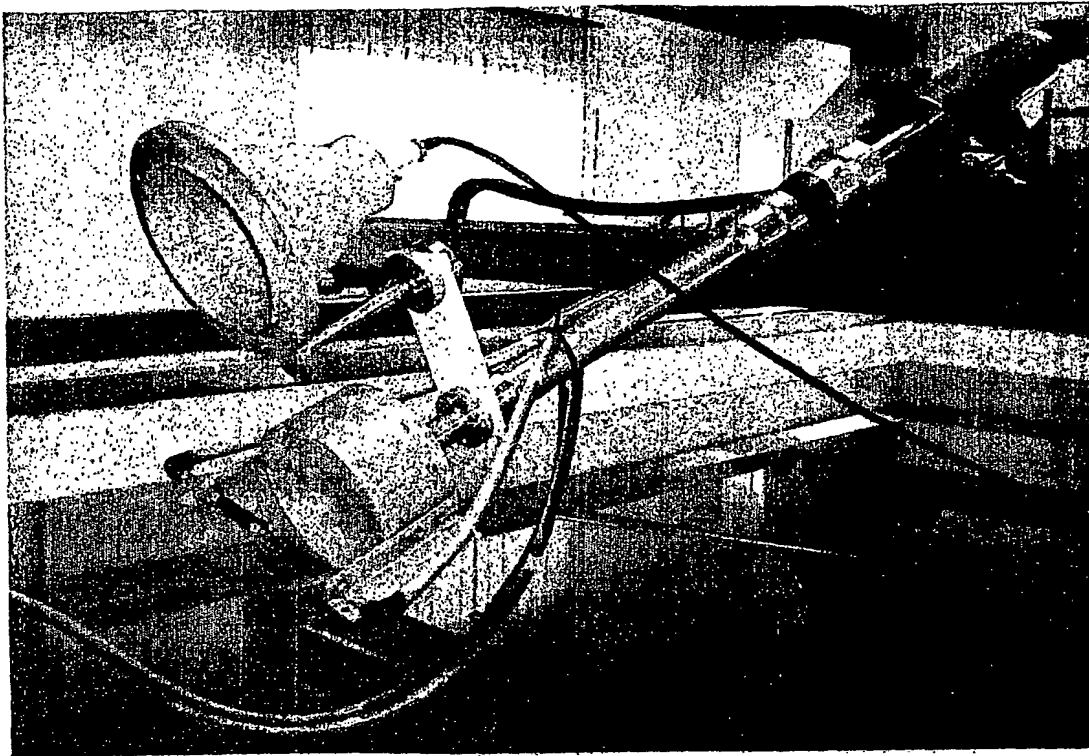


Fig 6

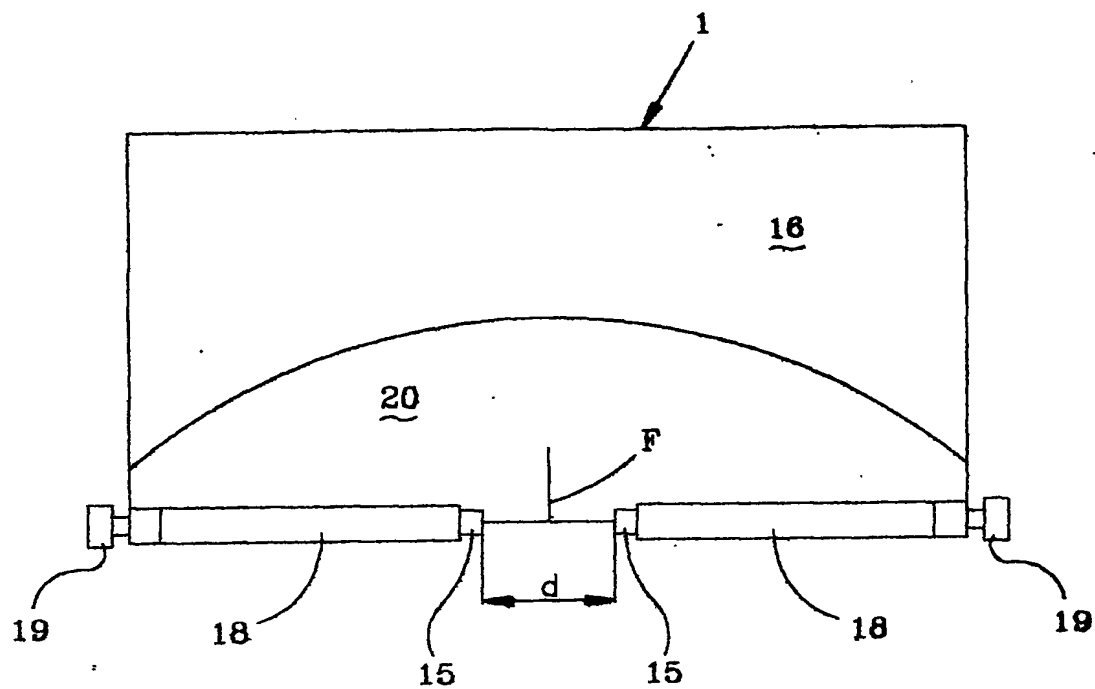


FIG. 7

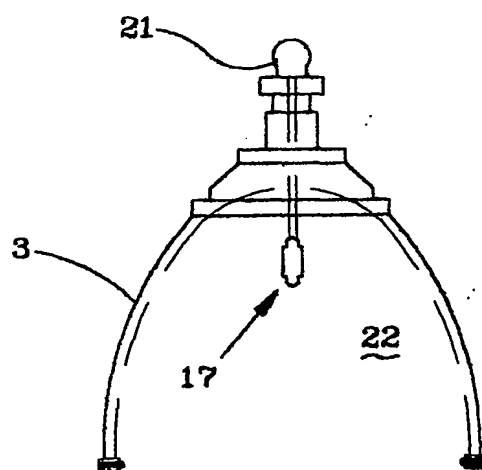


FIG. 8

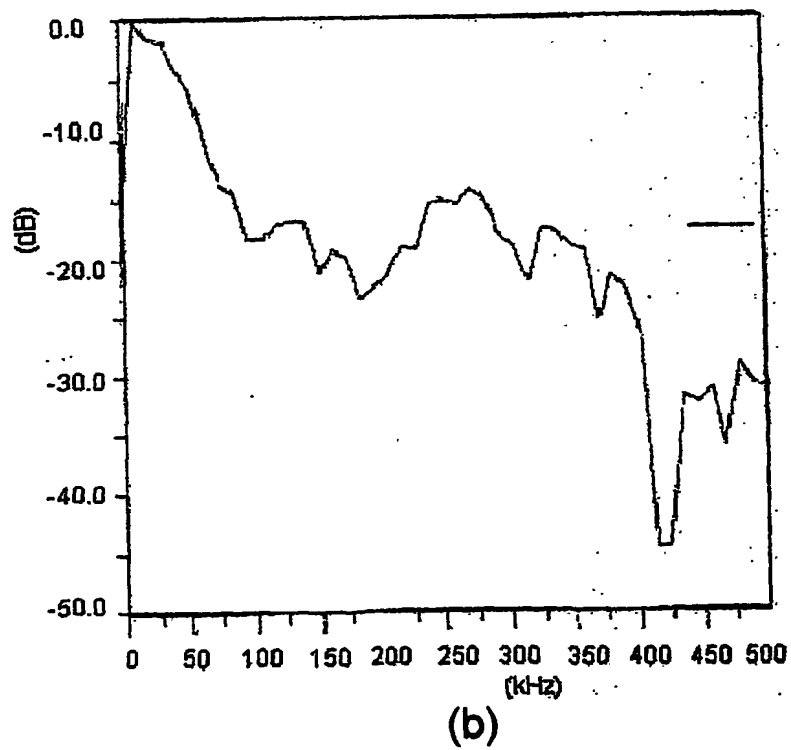
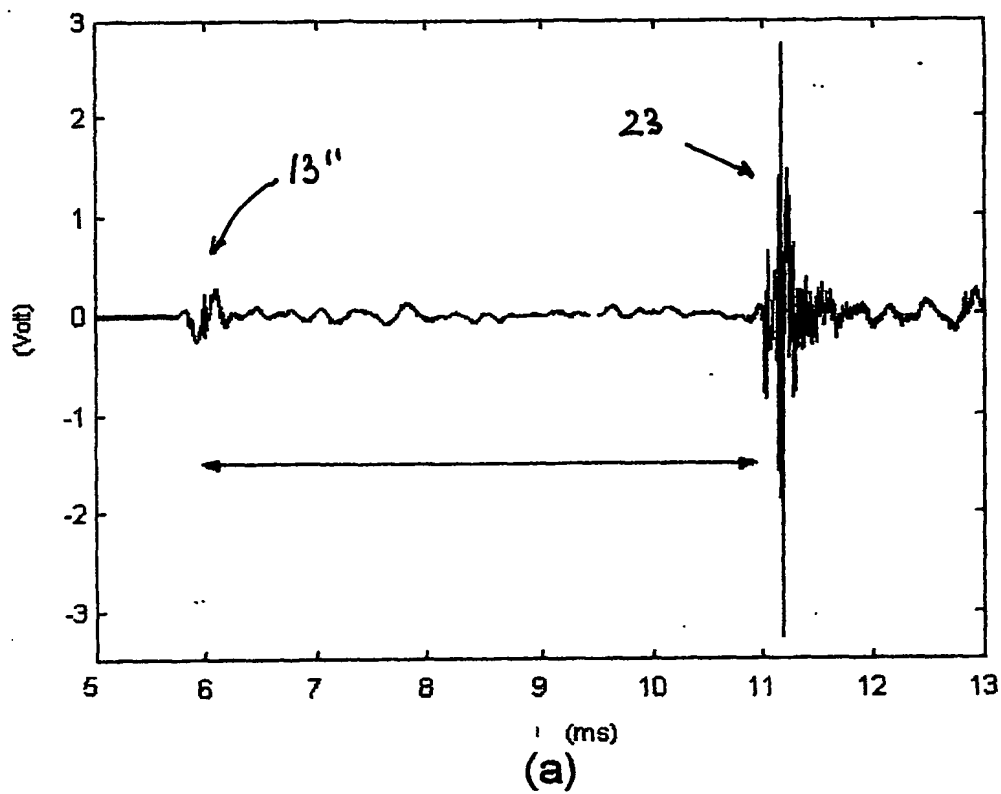
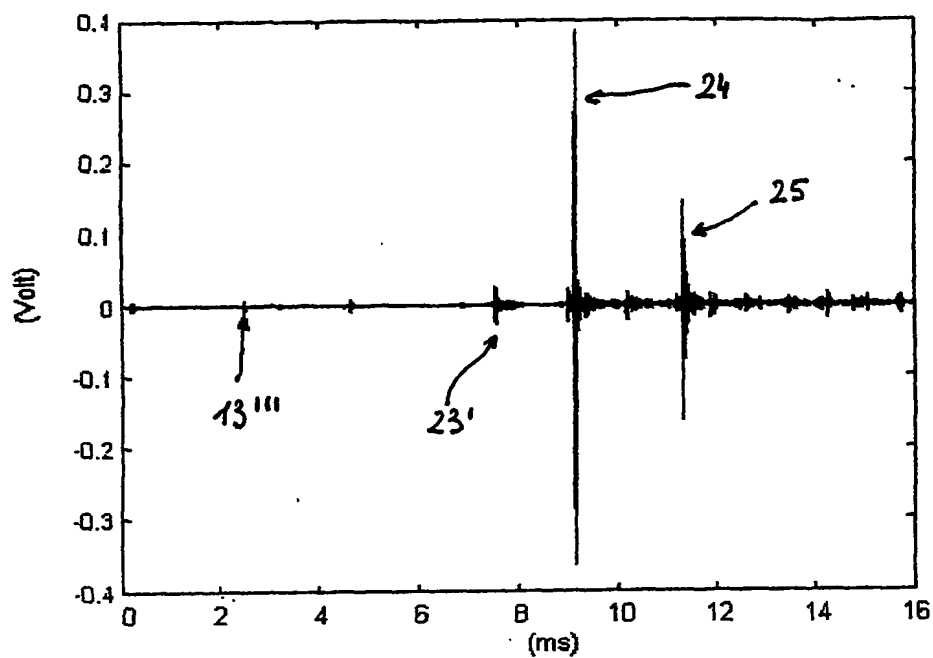


Fig. 9



(a)

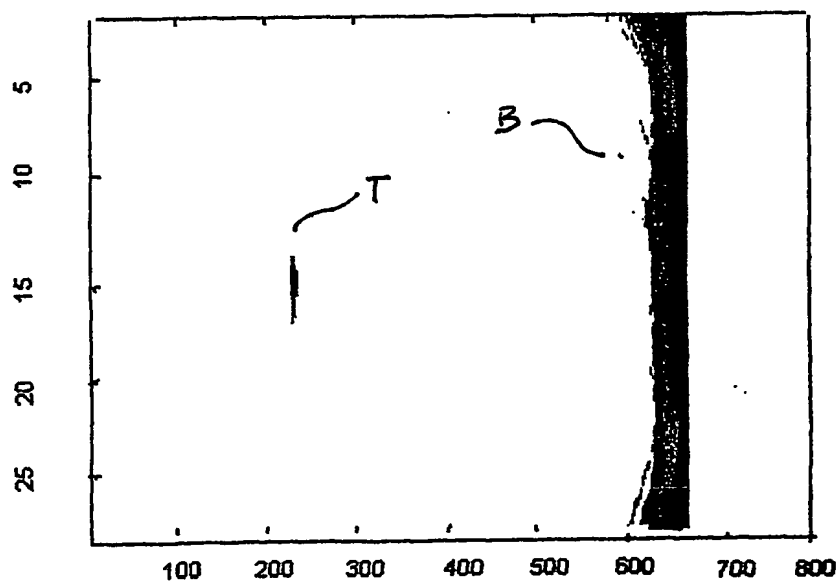
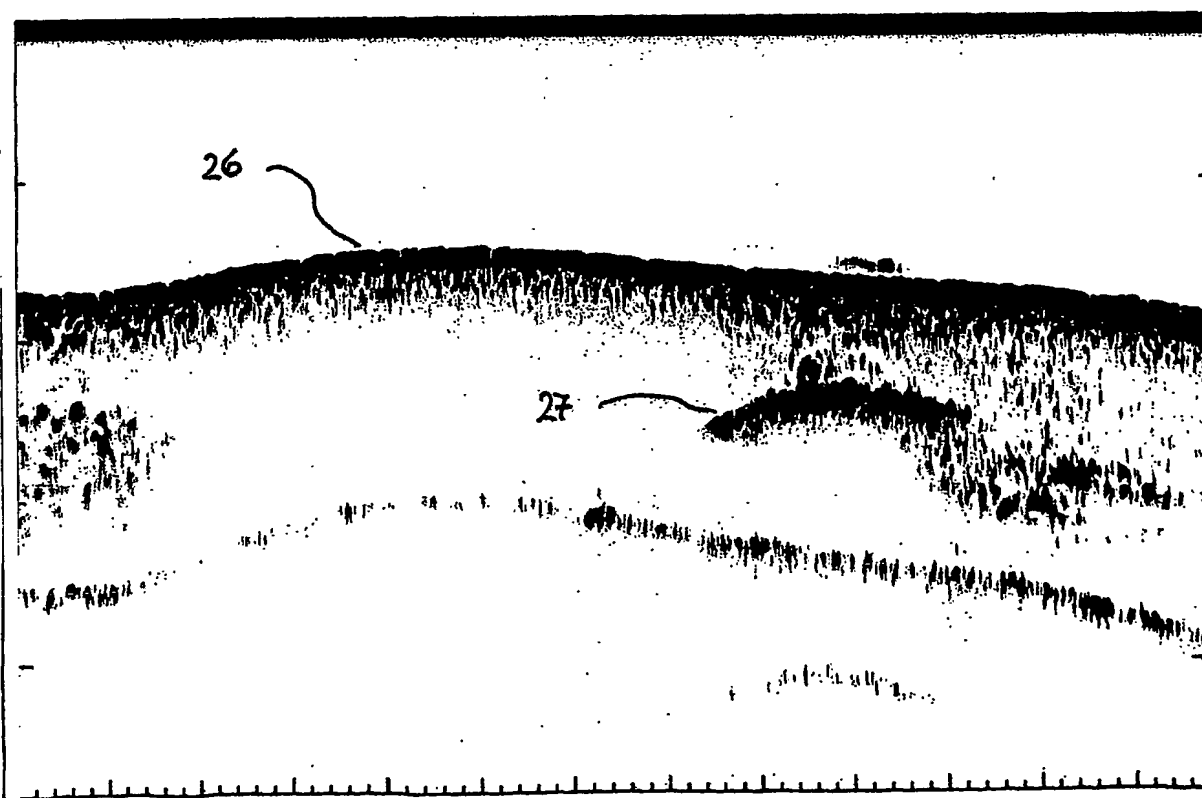
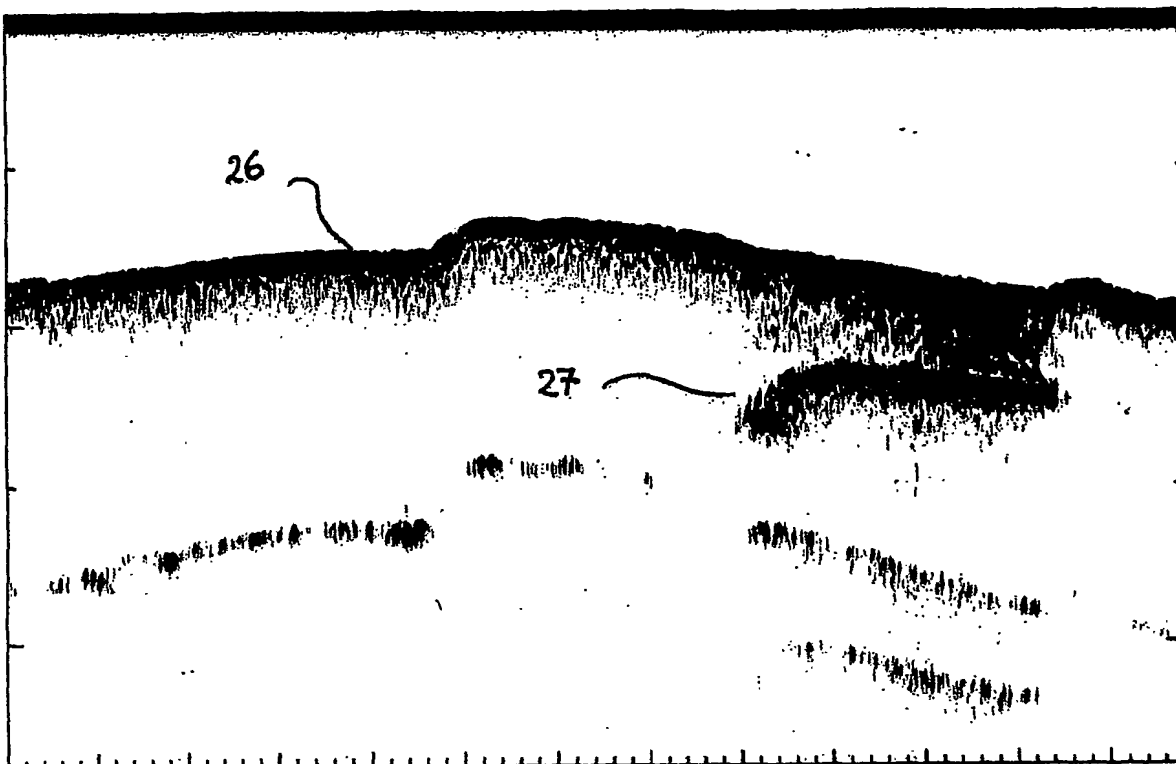


Fig 10

(b)

Fig. 11





## INTERNATIONAL SEARCH REPORT

International Application No.

PCT/IT 03/00751

A. CLASSIFICATION OF SUBJECT MATTER  
IPC 7 G01V1/157

According to International Patent Classification (IPC) or to both national classification and IPC

## B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

IPC 7 G01V

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

EPO-Internal, WPI Data

## C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	EP 0 320 466 A (CONSIGLIO NAZIONALE RICERCHE) 14 June 1989 (1989-06-14) column 6, line 8 - line 56 column 8, line 19 - line 56	8-15
A	claim 1	1-7
Y	FR 1 395 127 A (DYNA PULSE) 9 April 1965 (1965-04-09) page 3, left-hand column, line 36 - line 54	8-15
A	US 4 734 894 A (CANNELLI GIOVANNI B ET AL) 29 March 1988 (1988-03-29)	1-7
Y	column 4, line 12 - column 5, line 1	8-15
A	US 4 868 791 A (CATHIGNOL DOMINIQUE ET AL) 19 September 1989 (1989-09-19) column 5, line 12 - line 53; figure 1	1-15



Further documents are listed in the continuation of box C.



Patent family members are listed in annex.

## \* Special categories of cited documents:

- \*A\* document defining the general state of the art which is not considered to be of particular relevance
- \*E\* earlier document but published on or after the international filing date
- \*L\* document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)
- \*O\* document referring to an oral disclosure, use, exhibition or other means
- \*P\* document published prior to the international filing date but later than the priority date claimed

- \*T\* later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
- \*X\* document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
- \*Y\* document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.
- \* & \* document member of the same patent family

Date of the actual completion of the international search

24 March 2004

Date of mailing of the international search report

02/04/2004

Name and mailing address of the ISA

European Patent Office, P.B. 5818 Patentlaan 2  
NL - 2280 HV Rijswijk  
Tel. (+31-70) 340-2040, Tx. 31 651 epo nl,  
Fax: (+31-70) 340-3016

Authorized officer

Thomas, J

## INTERNATIONAL SEARCH REPORT

Information on patent family members.

International Application No.

PCT/IT 03/00751

Patent document cited in search report		Publication date	Patent family member(s)	Publication date
EP 0320466	A	14-06-1989	IT 1211963 B AT 77156 T CA 1316249 C DE 3871922 D1 DE 3871922 T2 EP 0320466 A2 ES 2033010 T3 GR 3005287 T3 JP 2077675 A US 4899845 A	08-11-1989 15-06-1992 13-04-1993 16-07-1992 03-12-1992 14-06-1989 01-03-1993 24-05-1993 16-03-1990 13-02-1990
FR 1395127	A	09-04-1965	NONE	
US 4734894	A	29-03-1988	IT 1178206 B AT 65613 T AU 5065385 A CA 1250040 A1 DE 3583617 D1 EP 0230415 A1 WO 8602739 A1 JP 4008755 B JP 62500685 T	09-09-1987 15-08-1991 15-05-1986 14-02-1989 29-08-1991 05-08-1987 09-05-1986 18-02-1992 19-03-1987
US 4868791	A	19-09-1989	FR 2612345 A1 AT 59739 T DE 3861339 D1 DE 285469 T1 EP 0285469 A1 GR 3001590 T3 IL 85620 A JP 1231973 A	16-09-1988 15-01-1991 07-02-1991 30-03-1989 05-10-1988 23-11-1992 29-03-1992 18-09-1989

**This Page is Inserted by IFW Indexing and Scanning  
Operations and is not part of the Official Record**

**BEST AVAILABLE IMAGES**

Defective images within this document are accurate representations of the original documents submitted by the applicant.

Defects in the images include but are not limited to the items checked:

- ☐ BLACK BORDERS
- ☐ IMAGE CUT OFF AT TOP, BOTTOM OR SIDES
- ☒ FADED TEXT OR DRAWING
- ☒ BLURRED OR ILLEGIBLE TEXT OR DRAWING
- ☐ SKEWED/SLANTED IMAGES
- ☐ COLOR OR BLACK AND WHITE PHOTOGRAPHS
- ☐ GRAY SCALE DOCUMENTS
- ☐ LINES OR MARKS ON ORIGINAL DOCUMENT
- ☐ REFERENCE(S) OR EXHIBIT(S) SUBMITTED ARE POOR QUALITY
- ☐ OTHER: \_\_\_\_\_

**IMAGES ARE BEST AVAILABLE COPY.**

**As rescanning these documents will not correct the image problems checked, please do not report these problems to the IFW Image Problem Mailbox.**